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WATER QUALITY DETERMINATION BY PHOTOGRAPHIC ANALYSIS

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Abstract

The culmination of many years work has lead to new and efficient aerial reconnaissance techniques to extract water quality parameters from aerial photos. A positive correlation exists between optical densities on film and turbidity in water. The turbidity can be correlated with total suspended solids if the constituent parts of the effluent remain the same and the volumetric flow remains relatively constant. The technique described requires the use of a monochromator for the selection of the bandwidths containing the most information. White reflectance panels are used to locate sampling points and eliminate enherent energy changes from lens flare, radial lens fall-off, and changing subject illumination. Misleading information resulting from bottom effects is avoided by the use of Secchi disc readings and proper choice of wavelength for analyzing the photos. The techniques described are derived from research with low flying aircraft similar to those which might be used for operational water quality monitoring. The same general principles can also be applied to high altitude photographs and satellite imagery. Some of the hardware and film analysis have application in other areas, such as soil and vegetational mapping.

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Introduction

The University of Wisconsin Department of Civil and Environmental Engineering has participated since 1968 in a National Aeronautics and Space Administration Grant (No. NGL 50-002-127) for Multidisciplinary Research in Remote Sensing as Applied to Water Quality. A project was started (in conjunction with the Wisconsin Department of Natural Resources) to find a more efficient means of monitoring paper mill waste effluents in Wisconsin's rivers. River surveys within the State of Wisconsin are currently made once every five to seven years. It was hoped that some of the parameters of water quality could be determined from quantitative analysis of aerial photographs.

The experience gained from the taking of aerial photographs and sampling over the last three years at the University of Wisconsin has led to new and imaginative aerial reconnaissance and data extraction techniques. A useful and usable system has been developed by the combination of laboratory and field results.

A well-defined plume was selected because of the strong interdependence of variables that affect mixing. The plume was located in a stream that was thought to have basic mixing characteristics when compared to other outfalls observed in the state. Because the color of the outfall was white, it was felt that the unique whiteness and near homogeneity would make analysis simpler.

The whiteness was caused by bleached organic fibrous material and a clay paper coating material suspended in the river water. The clay coating contains titanium dioxide (Rutile), a material used to add whiteness to the finished paper product.

Turbidity, an optical property, is related to light scattered from suspended material in the water. The suspended material causing the turbidity settles out of the stream forming a thick mat of clay and organic material. The waste from the particular site selected had an organic content of 30%. The organic portion of the mat creates a high biological oxygen demand (BOD) that causes anaerobic conditions on the stream bottom. These conditions will not support the usual flora and fauna of a healthy stream. Fish eggs will not survive in the altered bottom environment. At the time of the data collection, 27.5 tons of material per day were entering the stream. This caused a BOD_5 of 18,300 pounds per day. If this amount of material and its resultant stream degradation is permissible under current statutes, then better standards with improved surveillance and monitoring techniques are needed.

Sampling

Water samples were gathered at the time of the aerial photography. The samples were taken in the outfall and coverage extended downstream until the plume was indistinguishable from the background as observed from the air. Twenty-two-inch white styrofoam panels were anchored in the water prior to sampling to identify the sample points and eliminate the need for surveying the sample points and later relocating them photogrammetrically on the film. The white panel also served as a reference standard to eliminate the effects from variations in incident energy caused by time of day, time of year, and cloud conditions. The white panel can also serve as a standard to eliminate effects from radial lens falloff and lens flare; both are factors affecting the exposure. In all cases, the white panel was used as a known scene reflectance standard.

Bottom effects can mask the effluent and obscure the plume. A thorough understanding of the bottom effects should be known in the locations where sampling will occur. Secchi disc readings were used to find locations where the bottom reflection is significant. The Secchi disc consists of a white disc which is lowered into the water until it is no longer visible. This depth is known as the Secchi disc reading for that body of water. It is known that 1% of the return energy comes from below the depth of the Secchi disc reading.[1] The areas where the disc touches the bottom should be marked and eliminated from the analysis because of the effects of the bottom.

Water samples taken at the time of photography were analyzed in the laboratory for total solids, turbidity and color. Replicate samples at each point increased confidence in the sampling results. Random samples were split in the field to check reproducibility of laboratory results and equipment. The samples should be refrigerated upon collection and remain so until analyzed.

Photography and Processing

Nine inch vertical photographs were taken simultaneously with the water samples. A 9-inch mapping camera was outfitted with a 6-inch focal length lens, Kodak 8443 film, and with a No. 12 Wratten filter. Mid-afternoon was chosen to eliminate sun glitter, although in this particular case it turned out to be moderately overcast. The film-filter combinations were chosen on the basis of previous work.[2] Color infrared film was chosen because the infrared energy showing up as red on the film penetrates but a few inches into the water. Analyzing the red layer of the color infrared film essentially allows one to sense only the first few inches of water and completely eliminate bottom effects. One can also analyze the blue-green layer if greater depth penetration is preferred.

Film processing must be done by a processor familiar with sensitometric procedures.[3] A step wedge must be processed with the film because of the variations of films and processing. The area of the film that contained sampling locations was processed so as to fall in the linear portion of the D-log E curve. See Fig. 4 for a description of the D-log E curve.

Film Analysis

A Gamma Scientific microdensitometer-spectrophotometer was used to extract the quantitative information from the film.[4] One of the authors[5] designed an x-y scanning stage to modify the manufacturer's existing equipment. The stage is capable of holding bulk film up to a 70mm format and with the addition of a vacuum platen will hold single frames of nine-inch imagery. (See Fig. 1)

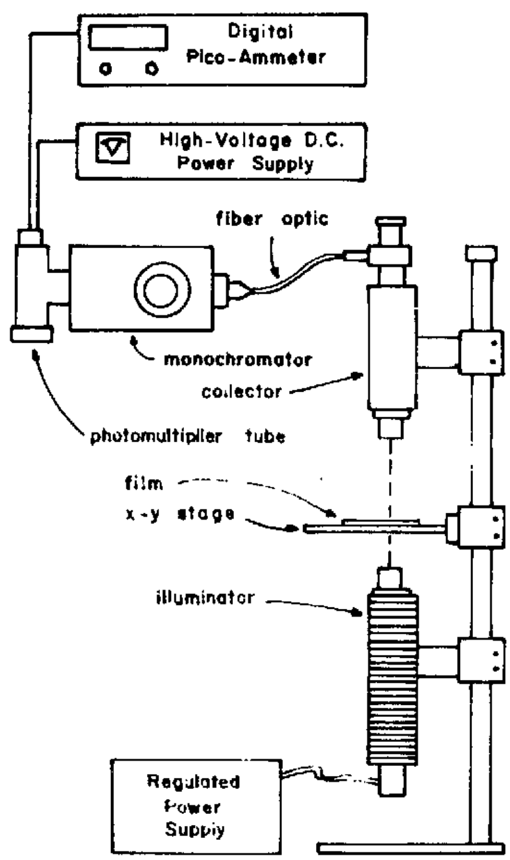


Fig. 1 Block diagram of film analysis system.

WATER QUALITY DETERMINATION

A collimated light source is focused onto the plane of the film. The equipment is equipped with various sized aperatures. A 50 micron spot was used for the analysis. This is equivalent to an area of 0.3 m^2 on the water's surface. The light energy, after illuminating a spot, is focused into a collector which reflects the energy into a fiber optic. The fiber optic is coupled to a Bausch and Lomb monochromator. A photomultiplier tube (PMT) is connected to the monochromatic output and the output of the PMT is then displayed on a digital pico-ammeter and the values can be used to measure specular transmittance and, therefore, density. Density values are computed as follows: $\text{Density} = \log_{10}\frac{1}{T}$ (1)

$$\text{where} \quad T = \frac{\text{Transmitted Light}}{\text{Incident Light}} = \text{Transmittance} \qquad (2)$$

Dark current readings should be subtracted from values. Raw outputs (transmitted light) were obtained as shown in Fig. 2.

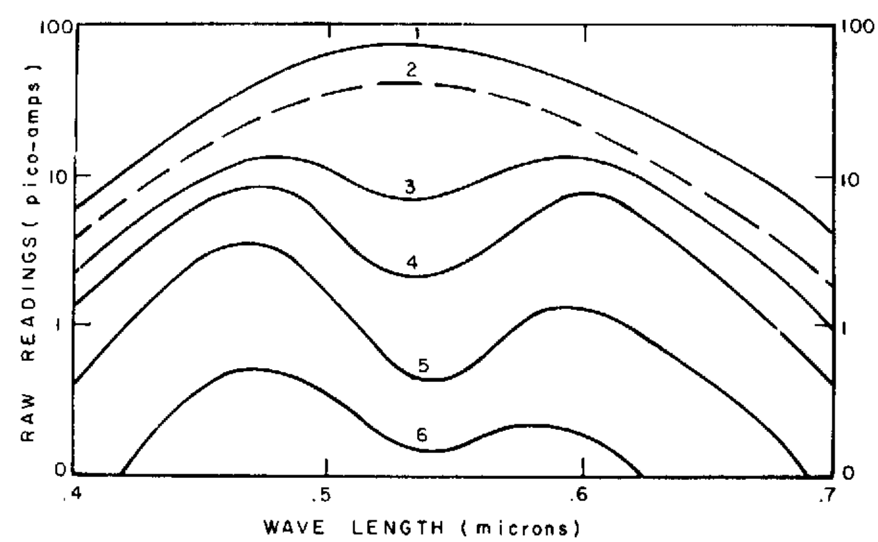


Fig. 2 Raw values from pico-ammeter.
1. Response of microdensitometer system (open air).
2. Theoretical response of white panel.
3. Typical response of white panel.
4. Typical high concentration of effluent.
5. Typical low concentration of effluent.
6. Background river water.

Raw readings show relative values. These values can be expressed in percent reflectance only when converted to densities and compared to a known scene standard.

A white surface reflects equally in all parts of the spectrum. A panel should theoretically have a response following that of the system. Instead it was found to have a "double-humped" nature as shown in number 3 of Fig. 2. This is explained by the inability of the color film's dyes to faithfully reproduce the full spectrum accurately. This limitation occurs because of the limited spectral bandwidth of each of the three dyes making up the emulsion. The relative performance of three dyes and their integrated effect is shown in Fig. 3.[6]

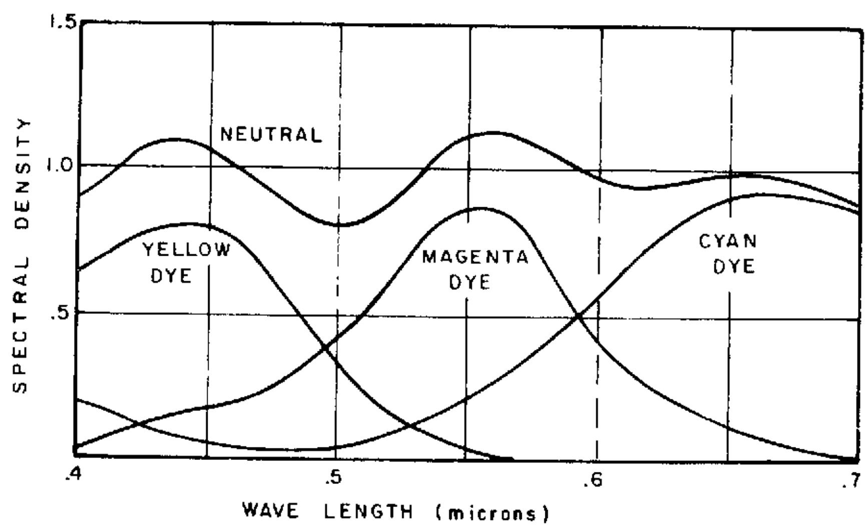


Fig. 3 Spectral dye density curve - Kodak Color IR 8443.

White light is composed of an equal amount of red, green and blue light. Greys or neutral densities are gradations of white. This effect further confirms the necessity for the use of white reflectance standards when using color films. A multispectral scanner which has a near linear response and gives absolute values referenced to skylight would eliminate the need for reflectance panels.

The D-log E curve is computed from the step wedge. The density of each step must be known. One must be careful to measure densities on the step wedge at the wavelength chosen for analysis because of changes in the slope of the D-log E curve with respect to wavelength in order to compensate for the spectral changes in dye sensitivities.[7] By the use of the D-log E curve for reversal film one can work from the densities through the curve and compute the relative intensities which caused the original exposure. (See Fig. 4)

Zero density units correspond to 100% transmission and three density units correspond to 0.1% transmission. The density or transmission values from the film are plotted on the ordinate or y-axis and the relative amounts of light causing these densities or transmittance values are shown on the abscissa or x-axis.

The white panel on the film is assumed to be 100% reflectance and the range of values from the effluent are compared to it. This yields values of 56% for the high concentrations of the effluent and 6% for the background water. In reality the reflectance of the white panel may be lower. Pending work measuring absolute values of reflectance referenced to sun and skylight will determine the actual field reflectance value of the panel.

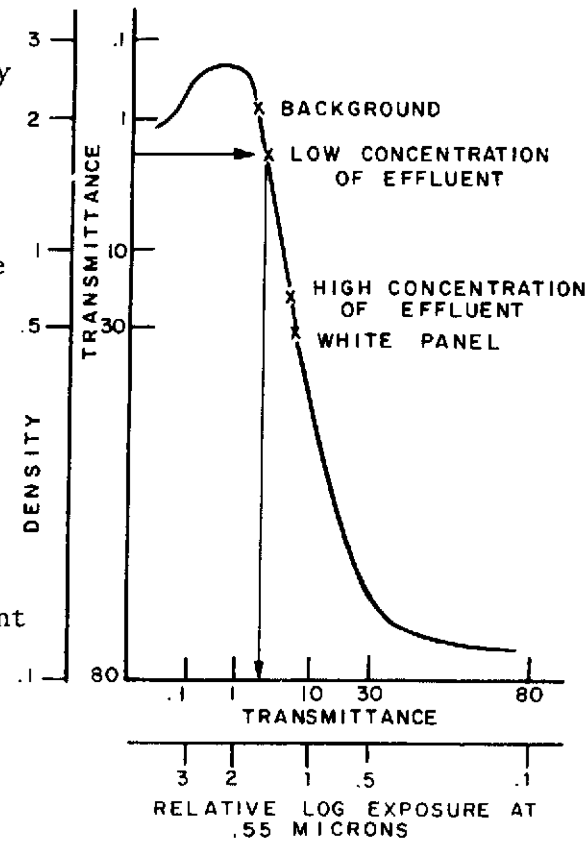


Fig. 4 D-log E curve for Kodak 8443 (reversal film). Relative exposure derived from step wedge.

Laboratory Analysis

Laboratory reflectances of water samples were obtained by attempting to duplicate field conditions in the laboratory. In this manner, laboratory data could be compared to field data. The styrofoam panels used in the field had a response almost identical to the laboratory standard (barium sulfate). (See Fig. 5.) This laboratory set-up measures surface volume reflectance—the reflectance related to turbidity.

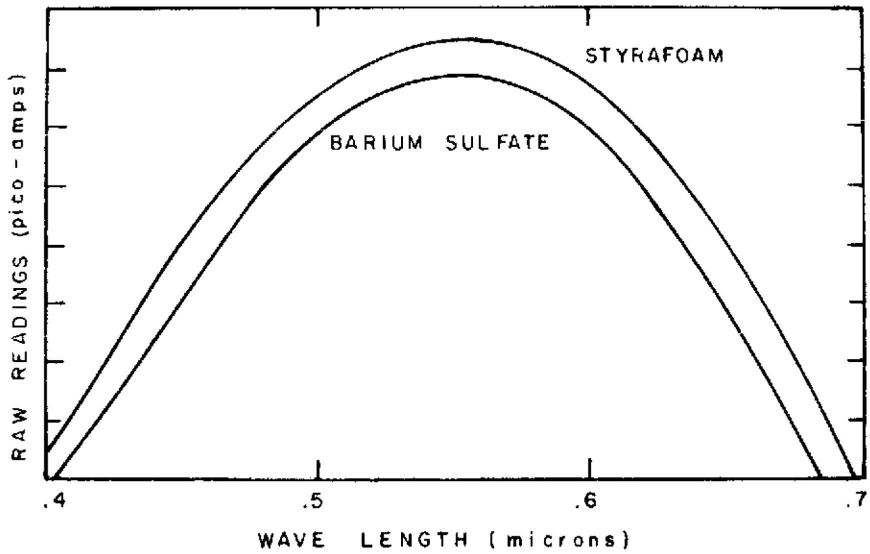


Fig. 5 Comparison of reflectance standards.

Figure 6 illustrates the layout of the laboratory appartus used to measure reflectance. This configuration uses the same PMT and Bausch and Lomb monochromator used in the film analysis, only now they are coupled to a telescopic head with an adjustable field of view.[8] (See Fig. 6)

The construction of the tube that holds the field samples is critical. While diameter does not have an important effect, the length, side material and bottom material play important roles. Secondary reflections occurred off a plain glass bottom. A flat black bottom was added to make bottom effects negligible. Shiny side material and sidelight increased reflectance to that representing field conditions. Reflectance was measured on dried waste effluent to achieve 1,000,000 ppm solids and also measured on dilutions of the waste that extended to that of tap water (0 ppm total suspended solids). Measurements were also made starting with tap water and adding measured amounts of titanium dioxide (Rutilc) until a saturation effect was achieved. The laboratory reflectance of high concentrations of the waste corresponded to values given in the Thermal Radiative Properties handbook for titanium dioxide. This confirmed our laboratory procedure.

Results

The slopes of the curves from the laboratory data were similar to the film when analyzed at the same wavelengths. (See Fig. 8) It was found that increases of turbidity or suspended solids caused increased reflectance. Turbidity is an optical property measuring scattered light, and is related only to suspended material and will not show dissolved substances. Turbidity is dependent on the wavelength used, the size and shape of the particles present, and their refractive index.[9]

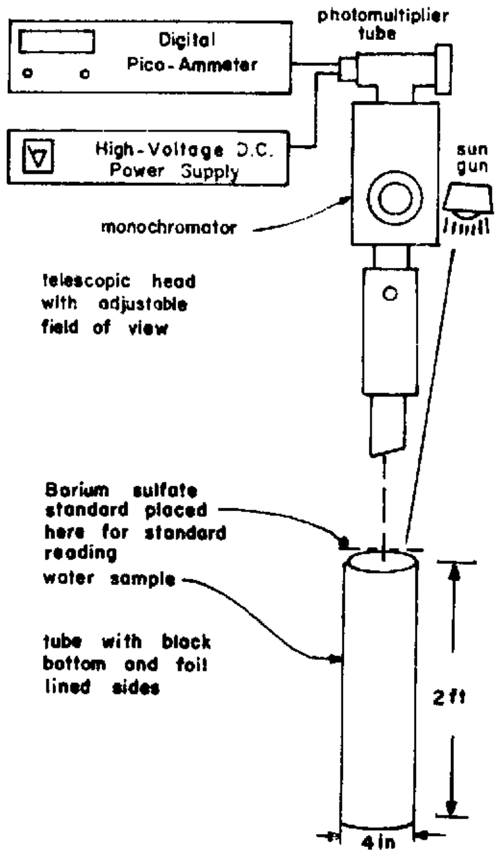


Fig. 6 Illustration of equipment for sample analysis.

Turbidity cannot be universally correlated to suspended solids, but for one type of effluent and constant flow rate, a correlation can be made. This is done by obtaining values from a standardized laboratory turbidimeter (Hach) and corresponding values from solids analysis from many sample points within the outfall. (See Fig. 7)

At a particular site turbidity can be correlated with reflectance over long periods of time provided the constituent material does not change and there is a continuous discharge. For point sources with intermittent discharges, such as a silt-laden stream discharging into a lake after a rainfall, the correlation can be made of turbidity to solids on a day to day basis; however, over long periods of time with no further discharge the suspended particle sizes become smaller due to settling and the correlation sought will also have to be based on such factors as settling rates. In other words, the correlation between reflectance and solids changes with time as the

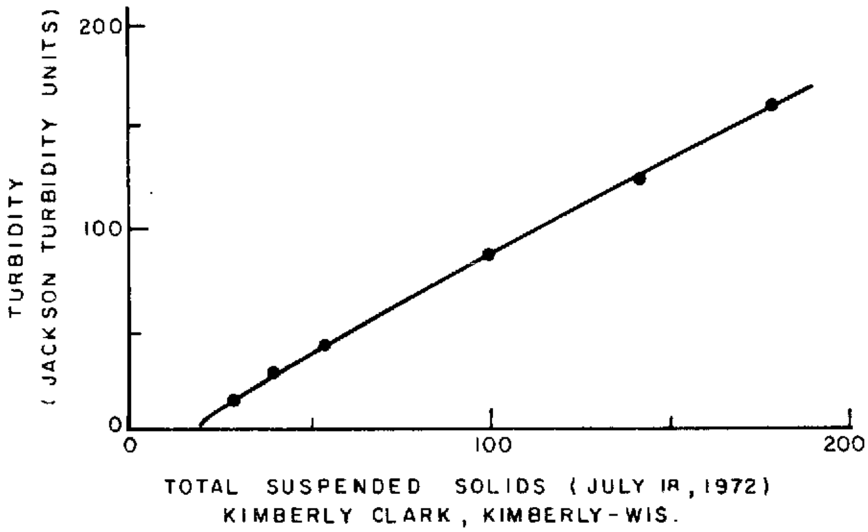


Fig. 7 Relationship of turbidity to suspended solids (ppm).

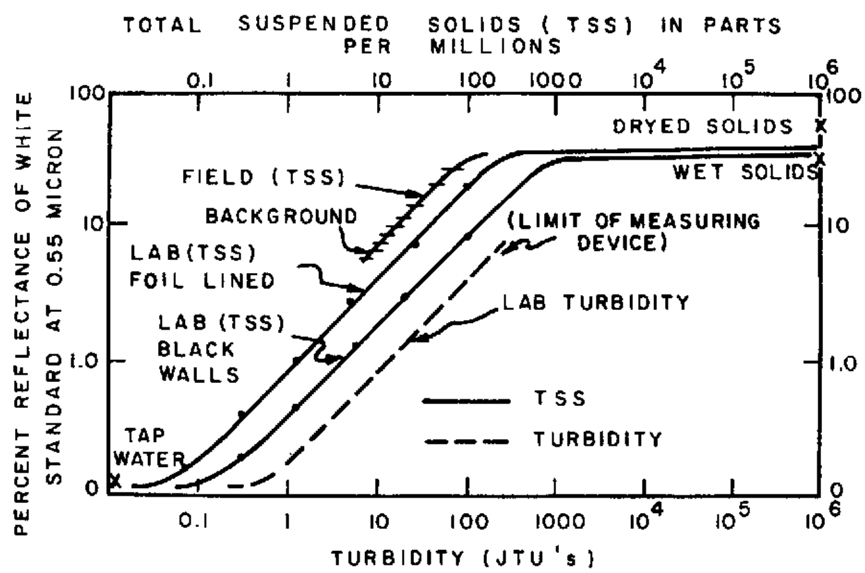


Fig. 8 Reflectance vs. turbidity and suspended solids. Field reflectance was obtained from film.

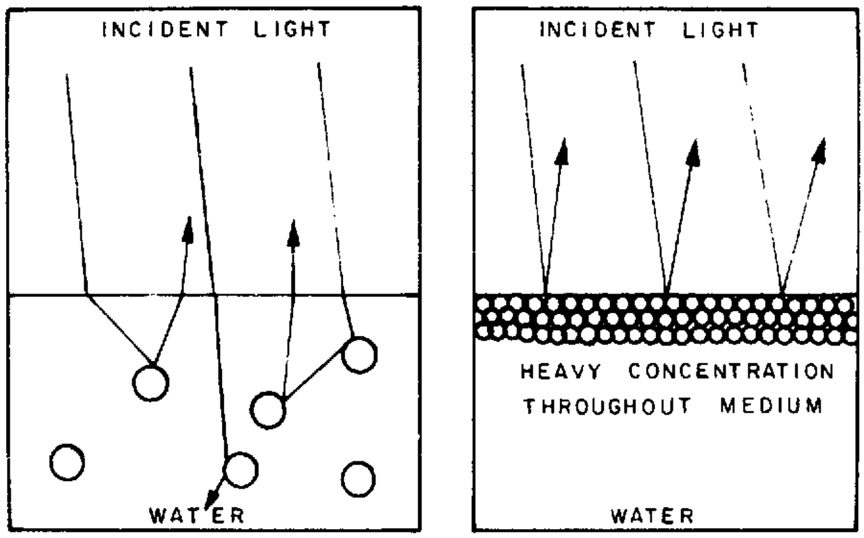
character of the solids change due to settling. The correlation between turbidity and reflectance appeared to be consistent for a particular waste regardless of time.

Turbidity is a measure of scattered light. By selecting a wavelength or wavelengths with the most information, a correlation was made between turbidity and response on the film (film densities). Because the effluent was white and had a flat response, excellent correlations were obtained over the entire visible spectrum. This occurred as long as the response was appreciably above the dark response of the photomultiplier tube.

In the laboratory a point was reached when increases in solids brought no further increases in the amount of scattered light returned to the sensor. Values of turbidity and reflectance did not increase as rapidly as thought. A similar flattening of the curve, when measured on the film, was also occurring very near the outfall. This is also the range where turbidity measurements are no longer obtainable with current laboratory equipment. (See Fig. 8)

Possible saturation of the film or PMT was thought to have occurred. Each was checked and both were found to be within their linear range. This phenomena can, however, be explained by the properties of light scattered in liquid mediums and from solids. Two types of scattering occur—single and multiple. While the pollutant levels are low, the scattering can be considered to be multiple (incoherent). As the level of pollutant increases in the effluent, the reflectance increases linearly until a certain level of concentration of the pollutant is reached; at that point, the reflectance no longer increases and further addition of the pollutant causes no further increase in reflectance. A saturation point has been reached and all the energy is being reflected back from the surface layer. This surface reflectance can be called single or coherent scattering. (See Fig. 9)

The additional input of sidelight (more energy) or the use of higher reflective sides (less absorption) in the laboratory sample tube made the reflectance values obtained higher and, thus, reached the saturation value sooner. By making the laboratory absorption and sidelight conditions representative of those in the field the corresponding curves moved closer together (Fig. 8). The unexplained remaining difference is most probably due to the skylight factor present in the field. The particular day analyzed was overcast causing the skylight factor to be very high. Pending work will hopefully answer this phenomena by subtracting representative values of skylight and side-scattered light from the field data to measure only surface volume reflectance.



Interfaces and absorption cause low reflectance. (Incoherent Scatterings)

Top layer closely compacted yields greater reflectance. (Coherent Scatterings)

Fig. 9

Conclusions and Recommendations

The combination of field data and laboratory analysis of paper mill wastes from the last three years has led to a positive correlation between optical densities on film and turbidity. The turbidity can be correlated with total suspended solids if the constituent parts of the effluent remain the same and the volumetric flow remains relatively constant. A photograph, if handled correctly, can be used for quantitative and qualitative work. Through the use of these developed techniques, less time is required in the field, thus allowing more complete and extensive surveys. Prior to these results it was assumed that to obtain a reliable correlation between photography and water conditions one must have extensive simultaneous sampling and photography over a large area. Now it seems necessary that only a minimal amount of ground truth and one or two passes with overlapping photography is necessary. It is theorized that only four samples and their replicates be taken. Typical points would be: 1) in the heaviest part of the effluent, 2) two points, spaced out, downstream from the source and in the plume, and 3) background water near where the effluent enters. The sample from the heaviest part of the effluent would be successively diluted in the laboratory to obtain the slope of the reflectance versus turbidity curve for that particular site. (See Fig. 8.) The other samples taken within the plume are used to establish the horizontal position of the turbidity versus reflectance curve as obtained from the film. This is necessary because of the skylight conditions which make it unreliable to translate laboratory reflectance directly to values from the photographs at this time. At a later time when a thorough understanding of skylight and related effects are known, it may be necessary to take only one water sample.

Other water quality parameters such as solids and color can be monitored from the film to whatever extent they correlate with turbidity. It is the parameter of turbidity that the aerial camera detects.

Acknowledgements

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% Reflectance of Sample Points
As Compared to a White Panel